Market-Based Monetary Policy Uncertainty*

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Abstract

Monetary policy announcements are surrounded by substantial uncertainty about the type, direction and magnitude of the policy action. Using a novel, market-based measure of monetary policy uncertainty we document a systematic, predictable pattern over the course of the FOMC meeting cycle: FOMC announcements lead to substantial resolution of uncertainty, which then gradually ramps up over the intermeeting period. Changes in uncertainty about the future policy path capture a distinct second dimension of monetary policy actions that is relevant for the transmission to financial markets. In particular, the Federal Reserve's forward guidance announcements affected asset prices not only by adjusting the expected policy path but also by changing market-perceived uncertainty about this path.

Keywords: monetary policy uncertainty, monetary transmission, Eurodollar options, implied volatility, event study

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1 Introduction

In early December 2008, the target for the federal funds rate stood at one percent. Implied probabilities extracted from fed funds futures options on March 2009 contracts indicated that having a target rate at that time either close to the zero lower bound or at 75 basis points was about equally likely with an implied probability of roughly 40% each.[1] On December 16, 2008, the FOMC cut the rate aggressively and established the target band of zero to 25 basis points and clearly communicated that the committee expects “low levels of the federal funds rate for some time.” Following the release of the FOMC statement, market prices reacted dramatically. Interest rates fell and the option-implied probabilities for a reversal of the rate cut dropped to below 10%, meaning that the market assigned roughly 90% probability to rates remaining at the zero lower bound through at least March 2009. This episode is an example of a substantial change in uncertainty about monetary policy: The rate cut and the corresponding clear forward guidance caused uncertainty about the future path of the policy rate to drop considerably. This manifested itself in the change in the above-mentioned option-implied probabilities, but can be seen more clearly by market-based measures of the uncertainty about future short rates. In this paper we propose a novel measure of this uncertainty, the standard deviation of the market-based distribution of the short rate one year into the future, derived from prices of interest rate options. Around this crucial FOMC meeting in December 2018 this distribution became substantially more concentrated around its mean, as indicated by a drop of 0.11 percentage points in our measure, one of the largest drops in our entire sample of days with FOMC policy announcements.

There is a large literature that studies the effects of changes in *expectations* for the future path of monetary policy on financial markets with an ingenious identification scheme using high-frequency changes in asset prices going back to Kuttner (2001).[2] However, the role of second moments and uncertainty in the transmission of monetary policy to financial markets has received much less attention. How do policy actions change the *uncertainty* around the expected policy rate path, and what are the effects of such changes on financial markets? These are the questions this paper is focused on. To be sure, measurement and macroeconomic effects of monetary policy uncertainty have been studied in some recent papers, in particular Husted, Rogers, and Sun (2016) and Creal and Wu (2017). But the uncertainty measures employed in the literature are generally based on surveys, text analysis of newspapers analysis, internet searches, or statistical/no-arbitrage models of interest rates, and they cannot be used for

[1] These option-based (risk-neutral) probabilities were calculated by the Federal Reserve Bank of Cleveland and reported on their website.

[2] See Bernanke and Kuttner (2005) or Gürkaynak, Sack, and Swanson (2005) among many others.

high-frequency identification of the effects of monetary policy.[3] In this paper, we propose a high-frequency measure of uncertainty about future monetary policy which allows us to study how uncertainty behaves around FOMC announcements. We document several new stylized facts about the interrelation of policy actions, policy uncertainty and financial markets: (i) Federal Reserve policy actions tend to substantially reduce uncertainty about future short-term interest rates, (ii) while uncertainty declines on average on announcement days, it drops more when the Fed eases monetary policy relative to market expectations, (iii) uncertainty gradually increases over the course of the FOMC meeting cycle, and (iv) changes in policy uncertainty on days with FOMC announcements have important effects on financial markets that are distinct from the changes in the expectations for the future policy rate, in particular during the post-crisis period.

Our measure of monetary policy uncertainty is based on prices of Eurodollar futures and options, and it estimates the conditional, risk-neutral standard deviation of the short-term interest rate at a fixed future horizon, say one year, given today's prices. To obtain a flexible, non-parametric estimate we apply the model-free implied volatility approach of Britten-Jones and Neuberger (2000) to Eurodollar derivaties and translate the implied volatility into the risk-neutral deviation of the future level of the policy rate. What separates our measure from existing measures of interest rate uncertainty or volatility is the focus on the uncertainty about short-term interest rates. Some well known measures of implied volatility from the fixed income market are based on short-maturity options on long maturity Treasury securities: the MOVE index is based on options on Treasury securities, while the TIV of Choi, Mueller, and Vedolin (2017) and the TYVIX index of the Chicago Mercantile Exchange are calculated using options on Treasury futures.[4] Since long-term rates are affected by a multitude of factors driving demand and supply in the Treasury bond market, these measures reflect uncertainty about all these factors and not only monetary policy. Our measure, by contrast, is designed to explicitly capture uncertainty about the future path of short-term interest rates.[5]

Equipped with this novel uncertainty measure we first document that monetary policy uncertainty substantially and significantly drops on days with FOMC announcements. Hence, on average, FOMC actions lower the perceived uncertainty about the future path of short term interest rates, i.e., they lead to a *resolution of uncertainty*. This pattern is present in all

[3]Exceptions include Emmons, Lakdawala, and Neely (2006) who use options on fed funds futures to study the market's evolving expectations about monetary policy decisions in the mid 2000s, as well as Bundick, Herriford, and Smith (2017) and De Pooter, Favara, Modugno, and Wu (2018), to be discussed below.

[4]Choi, Mueller, and Vedolin (2017) show how to replicate a variance swap in the fixed income market and use these results to construct their volatility index using options on Treasury futures.

[5]Our measure reflects the market-implied distribution for the three-month LIBOR rate, and we carefully address the issue that during the financial crisis this rate deviated substantially from the Fed's policy rate using different sample periods where the spread between the two was stable.

sample periods we consider, and is robust to the exclusion of the most influential observations. We show that the largest changes in monetary policy uncertainty coincided with important news about the Fed's future policy plans in an intuitively interpretable way.

We also find that conventional monetary policy surprises, which reflect revisions to expected future policy rates, tend to be correlated with changes in the uncertainty about future policy rates. That is, when the FOMC announcement causes a hawkish surprise, uncertainty tends to fall less or may even increase. Differently put, the decrease in uncertainty is significantly larger on days with expansionary policy surprises than on days with contractionary surprises. Accounting for the direction of the surprise does not, however, alter the fact that on average uncertainty exhibits a substantial and statistically significant decline.

The cumulative decline in uncertainty is more than 3.5 percentage points, while the level of uncertainty only drifts down modestly over the course of our sample period. This raises the question of when uncertainty about future policy rates is created. We show that neither major macro announcements nor speeches by FOMC members are the culprits. Instead, uncertainty tends to gradually *drift up over the course of the FOMC cycle*, and in particular over the first two weeks following the day after the FOMC meeting. The systematic and predictable pattern in market-based monetary policy uncertainty over the FOMC cycle, with a sudden decline around announcements and gradual ramp-up thereafter, has not been previously documented. These results provide a new perspective on the FOMC meeting cycle, policy information flow, and systematic changes in monetary policy uncertainty.

We then study the transmission of monetary policy uncertainty to asset prices. Our focus is on whether changes in uncertainty (second moments) have additional effects on asset prices that are distinct from the effects of changes in expectations (first moments), i.e., of conventional monetary policy surprise measures. We find that changes in uncertainty have a modest but statistically significant effect on longer term bond yields, controlling for the monetary policy surprise. Furthermore, increases in monetary policy uncertainty have a significantly negative effect on the stock market, both in terms of a lower return on the S&P 500 index and in terms of an increase in the VIX, again over and above the effect due to the monetary policy surprise. Moreover, the US dollar appreciates when uncertainty increases. The effects of changes in policy uncertainty on asset prices are generally larger and more strongly significant during the post-crisis period. We dig deeper into these effects with an event study of major announcements of unconventional monetary policies, including quantitative easing and forward guidance.

Our evidence suggests that monetary policy is not only transmitted directly through changes in the level of short- and medium-term interest rates around policy announcements but that there is a second channel that works through second moments or changes in the uncertainty about the future path of rates. While Gürkaynak, Sack, and Swanson (2005) argue for distinguishing between surprises in current short-term rates (target surprise) and expected future short-term rates (path surprise), we show that another important distinction is between changes in the *level* of the expected policy path and in the *uncertainty* around this future path. This distinction is particularly important for gauging the effects of forward guidance. A central bank's forward guidance not only affects the expected policy path but also the market's uncertainty about the path. To capture both dimensions of forward guidance, it is important to measure policy uncertainty at high enough frequency as we do in this paper.

Many papers study the effects of monetary policy (and of FOMC announcements in particular) on asset prices, including those cited above. An important recent example is Nakamura and Steinsson (2018) who use high-frequency futures data to identify monetary policy shocks and they show that in response to an interest rate hike nominal and real rates increase whereas inflation expectations remain mainly flat.[6] But this literature generally focuses on changes in interest rates and expectations of future policy rates, that is, on first moments.

Three recent studies carry out event studies of FOMC actions with a focus on the role of second moments, uncertainty and risk, and are closely related to our work. Bundick, Herriford, and Smith (2017) study the effects of shifts in the term structure of monetary policy uncertainty on estimated term premia in long-term interest rates, and find a positive correlation between slope shifts and term premia. In addition, they document macroeconomic effects of changes in monetary policy uncertainty that are distinct from the effects of conventional policy surprises. De Pooter, Favara, Modugno, and Wu (2018) condition on the level of policy uncertainty in the usual event-study regressions, and find evidence that yields respond less to policy surprises when the level of uncertainty was previously high. Our study has a distinctly different focus compared to these two papers, as we document effects of FOMC policy actions on uncertainty, and the role of uncertainty in the transmission to a range of different asset prices. Like us, these papers also derive their measures of policy uncertainty from Eurodollar options, and we discuss the differences and benefits of our methodology below. Kroencke, Schmeling, and Schrimpf (2018) documents an "FOMC risk shift" as a separate dimension of FOMC announcement effects closely related to changes in risk spreads and the VIX, which they find to be correlated with stock returns. Overall, both the analysis and results in our paper are novel relative to other papers that use event studies to estimate the effects of Federal Reserve policy on financial markets.

[6] Hanson and Stein (2015) similarly find that hikes in nominal rates translate to an increase of real rates, noting that this is at odds with standard macro-models based on sticky prices. They conclude that the change in real rates is due to a change in term premia and they propose a channel based on yield-oriented investors.

Our paper is also related to the broader literature that studies the role of uncertainty and volatility for the term structure of interest rates. Volker (2017) uses survey data to measure uncertainty about monetary policy and shows in an affine no-arbitrage model that the monthly series of uncertainty is closely linked to the term structure of Treasury yields. Cieslak and Povala (2016) study the conditional volatilities of Treasuries and find that model-implied short-end volatility factor co-moves with monetary policy uncertainty. Choi, Mueller, and Vedolin (2017) investigate the link between the term structure of implied volatility and economic activity as well as stress in the financial markets. Mertens and Williams (2018) use caps prices to study the effects of the zero lower bound on long-term forecast densities of interest rates, focusing on a theoretical where inflation is determined by a fundamental shock, inflation expectations and the level of interest rates set by the central bank. These papers all touch on issues relating to the role of monetary policy uncertainty for interest rates, but none use high-frequency idetification of the effects of monetary policy on financial markets.

Finally, some recent papers have pointed out that overall market uncertainty as measured by the VIX tends to fall on days with FOMC meetings, see for example Amengual and Xiu (2018); Gu, Kurov, and Wolfe (2018); Hu, Pan, Wang, and Zhu (2018); Fernandez-Perez, Frijns, and Tourani-Rad (2017). Our results suggest that it is the change in uncertainty about future short rate decisions that is driving the change in overall market uncertainty.

The paper is structured as follows. In Section 2 we describe the construction of our market-based uncertainty measure and discuss its differences and benefits relative to existing measures. In Section 3 we investigate how FOMC policy actions affect the uncertainty about the future policy path and document both the resolution and ramp-up of uncertainty over the FOMC cycle. Section 4 investigates the role of policy uncertainty in the transmission of monetary policy to financial markets. The appendix includes additional results.

2 Measuring policy uncertainty using options

Our goal is to obtain a model-free measure of the uncertainty about future short-term interest rates, i.e., about the future path of the Fed's policy rate. This is possible using market prices of money market derivatives. Interest rates at different maturities can only provide estimates of the *mean* of investor beliefs about future policy rates, and rates on fed funds and Eurodollar futures are commonly used for this purpose. But to estimate the *uncertainty* around this mean, what we term "monetary policy uncertainty," we need to turn to option markets, where we can use prices of option contracts with the same expiration but different strikes to learn about the market-implied distribution of future policy rates. In this section we describe our market data and our methodology to construct our measure of uncertainty.

We base our uncertainty measure on prices of Eurodollar futures and options, which are contracts with payoffs tied to the three-month LIBOR rate.[7] The futures prices are from Bloomberg and the option prices are directly from the Chicago Mercantile Exchange. Our main reason to use Eurodollar futures and options data is the extremely high liquidity of Eurodollar futures and the very active related option markets. Futures and option markets also exist for contracts with the federal funds rate as the underlying instrument. An uncertainty measure derived from the prices of these contracts would have the benefit that it directly pertains to the future evolution of the Federal Reserve's policy rate. However, using fed funds options is impractical for our purpose because their market is much less liquid and the data availability much more limited, both in terms of historical time span and length of horizons of the derivative contracts. How big of a price do we pay by focusing on three-month LIBOR instead of the fed funds rate as the underlying? In general, the LIBOR rate has historically been closely tied to the federal funds rate and other money market rates, which is why it serves as the benchmark money-market rate for an enormous amount of derivative contracts (such as interest rate swaps) based on it. The difference between LIBOR and the fed funds rate is best measured by the LIBOR-OIS spread, which is calculated based on rates of the same horizon and considered as an indicator of financial stress.[8] Before the 2008 financial crisis, this spread was low and stable. For example, over the period from January 2002 to June 2007 it had a mean of 11 basis points and a standard deviation of 3.5 basis points. This spread spiked over the course of the financial crisis, as worries about the health of the banking system translated into dramatically increased interbank borrowing rates and hence the LIBOR rate. By the end of 2009 the LIBOR-OIS spread returned again to relatively low and stable levels, with only occasional and much less pronounced spikes. This suggests that outside of the financial crisis, uncertainty about future LIBOR rates mainly reflects uncertainty about future monetary policy. In order to ensure the robustness of our results against changes in uncertainty about LIBOR-OIS and financial stress, we report all of our empirical results not only for our full sample period but also for a pre-crisis sample period ending in June 2007 (before LIBOR-OIS increased dramatically), and a post-crisis period beginning in July 2009 (after LIBOR-OIS returned to a regime of relative stability).

Denoting by L_T the future three-month LIBOR rate, our main object of interest is the conditional variance $Var_t(L_T)$ under the risk-neutral (forward) measure, which we can esti-

[7]For detailed information see https://www.cmegroup.com/trading/interest-rates/eurodollar.html.

[8]The most commonly quoted LIBOR is for a three-month term, whereas the fed funds rate is an overnight rate. Rates on "Overnight Indexed Swaps" (OIS) with a three-month tenor reflect the market's (risk-neutral) expectation for the fed funds rate over this period, and are therefore the appropriate rate to compare three-month LIBOR to.

mate based on time-t prices of Eurodollar options and futures. Under the assumptions of the famous Black (1976) model, this would be completely straightforward: Since the futures rate, which we denote by F_t, is assumed to follow a geometric Brownian motion with instantaneous volatility σ, the distribution of L_T is log-normal and completely determined by F_t, σ, and the horizon $\tau = T - t$. Specifically, the Black model implies that $Var_t(L_T) = F_t^2[e^{\sigma^2\tau} - 1] \approx F_t^2\sigma^2\tau$, and we could simply back out the implied volatility (IV) σ from observed option prices.[9] There would be, however, two disadvantages to using this approach for our purpose: First, the strong parametric assumptions about the distribution of futures rates are unlikely to be satisfied in practice. Second, for a given underlying futures contract, each option contract (puts and calls at different strike prices) in practice has a different IV.

Instead of relying on a specific parametric model, we therefore use the model-free estimate of IV proposed by Britten-Jones and Neuberger (2000) and Jiang and Tian (2005). These papers show that the integrated return variance for a forward contract between t and T is

$$IRV_{t,\tau} = E_t\left[\int_t^{t+\tau}\left(\frac{dF_j}{F_j}\right)^2\right] = 2\int_0^\infty \frac{C^F(t,T,K) - \max(0, F_t - K)}{K^2}dK, \tag{1}$$

where $C^F(t,T,K)$ is the forward call price at time t with expiration $T = t + \tau$ and strike K, and F_t is the current forward rate. Since Eurodollar options are mark-to-market (no money changes hands at contract initiation) quoted prices are in fact forward option prices. The conditional expectation is taken under the risk-neutral time-T forward measure, under which the forward price F_t is a martingale (Choi, Mueller, and Vedolin, 2017). Note that the last expression in equation (1) is equivalent to the fair strike of a variance swap.[10] The annualized "model-free implied volatility" (MFIV) is $\sqrt{IRV_{t,\tau}/\tau}$. To gain intuition it is useful to consider the special case of the Black model, where $IRV_{t,\tau} = \sigma^2\tau$ and the MFIV is simply the Black volatility σ. Estimation of the MFIV does not require any parametric assumptions, and, as shown by Jiang and Tian (2005) is valid for general jump-diffusion processes. In our implementation we abstract from the facts that (i) the underlying are futures instead of forward contracts, and that (ii) Eurodollar options are American and not European options; experience suggests that accounting for these technicalities would lead to only minor adjustments.[11] The integral in

[9] Here we ignore the difference between futures and forward rates for ease of exposition.

[10] Choi, Mueller, and Vedolin (2017) derive an expression for the variance swap rate under stochastic interest rates, given in their equation (6). It is easily seen to be equivalent to equation (1) using the put-call parity for forward option prices, $C^F - P^F = F - K$ and the fact that the forward option price is the spot option price divided by the price of a zero-coupon bond.

[11] See Choi, Mueller, and Vedolin (2017). Furthermore, since we will only be using out-of-the-money (OTM) option contracts any adjustment for early exercise would be minimal, since the early-exercise premium increases with the moneyness of the option contract.

equation (1) can be approximated in a straightforward fashion using observed option prices: We use the formula given in equation (6) of Jiang and Tian (2005) and a smooth call-price function fitted to the options data. Specifically, for a given trading date and futures contract, we consider the prices of all OTM option contracts, and fit a cubic spline to the Black IVs. Translating these IVs back into call prices gives us a smooth call-price function for any desired strike price, allowing for numerical integration over a fine grid to approximate equation (1).[12] The only material difference with the approach of Jiang and Tian (2005) is that we use the Black formula instead of the Black-Scholes formula, since we are dealing with interest rate derivatives. Just like those authors we do not assume the validity of a specific option-price model, but instead just use it to fit a function in strike/implied-volatility space which is more reliable than fitting in strike/price space. With the call-price function in hand, we approximate the required integral using 20 grid points and an interval of 2 percent above and below the current futures rate (with a lower bound of zero).

Implied volatility generally pertains to the *return* on an asset, but we are interested in the volatility of the future *level* of the underlying interest rate. A simple way to translate from returns to levels is to multiply the implied volatility by F_t. That is, we estimate the risk-neutral standard deviation of the future short-term interest rate, conditional on prices at t, as $\sqrt{Var_t(L_{t+\tau})} = F_t\sqrt{IRV_{t,\tau}}$. For each trading day, we obtain this volatility estimate for all available quarterly contract expirations. We then calculate constant-maturity measures by linearly interpolating the volatilities from adjacent contracts to horizons of 0.5, 1, 1.5 and 2 years. This gives us four series of monetary policy uncertainty, denoted by $mpu_{t,\tau}$.

Figure 1 displays the resulting estimates. Several features are worth mentioning: First, there is considerable variation over the course of our sample. At the one-year horizon, for example, the measure ranges from about a quarter percent to two percent. Second, all measures were substantially elevated during the financial crisis, but dropped notably during the 2010-2014 episode when the Fed's policy rate remained close to zero and forward guidance about its future evolution was in place. Third, the measures at different horizons are quite closely correlated. For example, the correlation between the series for the 6-month and one-year horizons is 0.77. While we may in future work combine the information from uncertainty measures across different horizons, for example using the first principal component, the analysis in this paper simply uses the measure for the one-year horizon, denoted by mpu.

A large number of different measures of interest rate uncertainty, policy uncertainty, and monetary policy uncertainty have been proposed in the literature, and it is important to note how our measure improves upon existing ones. Since our main interest is on the financial

[12] For strikes outside the range of observed option prices we take the IV to be the same as the IV at the bounds.

market effects of central bank policy actions, we require the measure to be available at high frequency, i.e., at least daily. This rules out measures based on survey expectations of future interest rates, as used for example by Volker (2017) and Istrefi and Mouabbi (2017), since surveys are conducted at monthly or quarterly frequencies. Furthermore, for our purpose the recently developed uncertainty measures based on newspaper articles and internet searches, such as Husted, Rogers, and Sun (2016) for monetary policy uncertainty, are also inadequate, as these are available only at monthly frequencies. Similarly, estimates of policy uncertainty based on no-arbitrage yield curve models with stochastic volatility, such as Creal and Wu (2017), are generally available only at monthly frequency. While such models could in principle be estimated at a daily frequency, volatility is inferred (filtered) from the time series behavior of interest rates, which makes it problematic to use the resulting uncertainty estimates in high-frequency event studies.

To carry out any type of event study analysis with high-frequency identification of monetary policy effects, we need market-based measures of interest rate uncertainty, which estimate volatility from the cross section of option prices. A widely used market-based measure of interest rate uncertainty is the MOVE index, which is based on short-dated options (with expirations up to 30 days) on long-term Treasury bonds. A related but arguably more reliable measure is the TIV (also called TYVIX) index, developed by Choi, Mueller, and Vedolin (2017), which uses options on Treasury futures. While these measures are available at the daily frequency, these are inappropriate for our purpose for another important reason: They capture the (near-term) uncertainty about *long-term* interest rates, whereas we want to measure the uncertainty about *short-term* interest rates (mainly over the medium term). Short-term rates are determined by the Federal Reserve, and our intent is to measure the uncertainty about the Fed's policies. Long-term rates, by contrast, are affected by a multitude of factors, including on the one hand by expectations about future monetary policy, and on the other hand by the term premium which reflects all other supply and demand forces in Treasury markets. To avoid confounding uncertainty about monetary policy with uncertainty about various other drivers of bond prices, our measure needs to use prices of derivatives written on short-term interest rates, and Eurodollar options are the best choice for the reasons given above.[13]

Most closely related to our methodology is the paper by Bundick, Herriford, and Smith (2017), who also use Eurodollar options to measure uncertainty about future short rates is.[14] They apply the VIX formula to the prices of Eurodollar options. Our measure differs in several

[13]The fact that the TIV and the MOVE measure a different type of interest rate uncertainty is also apprent from the modest correlation with our measure: the correlation in levels with our one-year measure is 0.62 and 0.76, respectively, while the correlation of the daily changes is 0.26 and 0.45.

[14]De Pooter, Favara, Modugno, and Wu (2018) construct their measure of monetary policy uncertainty using the Black model (i.e., a log-normal distribution) and at-the-money option prices.

ways: First, we use a smooth call-price function, which generally gives a better approximation of the required integrals. Second, we translate the estimated IVs into volatilities about the future level of interest rates. Third, we account for the time-varying horizons of observed Eurodollar contracts and interpolate to a constant-maturity measure of uncertainty, focusing on a one-year horizon.

Given the current state of the literature, we view our methodology and resulting monetary policy uncertainty measure as an appealing choice that has certain benefits over existing methods and is well-suited to our aim of investigating the role of policy uncertainty for the transmission of monetary policy to financial markets.

3 Uncertainty over the FOMC cycle

We begin our investigation by studying the behavior of monetary policy uncertainty on days with FOMC announcements, and comparing it to the behavior on other days. Our sample from January 1994 to December 2017 includes 203 FOMC announcements days, 11 of which are unscheduled.[15]

Our first main result is immediately apparent from Figure 2, which plots the daily changes in *mpu* on FOMC days. The figure clearly shows that *mpu* falls on the vast majority of these days. Specifically, uncertainty falls on about three out of four days (154 out of 203). Table 1 reports summary statistics and shows that the average decline on FOMC dayswas 1.8 basis points, strongly statistically significant with a a p-value below 0.001. This significant decline on FOMC days stands in contrast to the average change on all other days, which is essentially zero. Moreover, the magnitude of the average decline on FOMC days is equal to about three quarters of the standard deviation of the daily changes in *mpu* across all days (which is 0.025) and more than half of the standard deviation on FOMC days (which is 0.032), meaning that the decline in uncertainty is both statistically and economically significant. Not very surprisingly, the difference of the average change in *mpu* on FOMC days and other days is also strongly significant.

Thus, the monetary policy announcements and actions of the FOMC on meeting days typically lead to a *resolution of uncertainty* about the future path of interest rates that is reflected in an average decline in *mpu*. Given that FOMC announcements include various pieces of information such as the committee's economic outlook, decisions about conventional and

[15] We drop the FOMC meeting on 17 September 2001 from our sample, as is commonly done in the event study literature due to the unique nature of this first meeting after 9/11. While we include all other unscheduled FOMC meetings, we note that all our results remain essentially unchanged when we exclude these days from our sample.

unconventional monetary policies, and communication about the likely future path of policy rates, that is, forward guidance, it is not a priori obvious how exactly policy announcements would affect uncertainty about the future policy path. On the one hand, one might argue that by providing more information about monetary policy, the FOMC makes market participants more confident in certain future scenarios, and helps coordinate them on a particular belief (Blinder, Ehrmann, Fratzscher, De Haan, and Jansen, 2008). On the other hand, FOMC announcements tend to create surprises and market volatility, as documented in the extensive literature on the effects of monetary policy surprises on financial markets (for example Gürkaynak, Sack, and Swanson, 2005; Bauer, 2015) and, therefore, may lead to higher uncertainty. Our results indicate that while FOMC announcements create additional volatility in financial markets in the short run, they tend to reduce expected future volatility according to market-based measured of uncertainty about future short rates.

Our sample includes the financial crisis of 2007–2008, a unique episode with unprecedented levels of uncertainty and monetary policy interventions. We therefore also consider a subsample that ends in June 2007 before the onset of the crisis, as well as one that begins in July 2009 after the crisis abated (see also the discussion in Section 2). Table 1 also reports summary statistics for these subsamples. For both the pre- and post-crisis samples results are very similar with significant declines in *mpu* on FOMC days and zero average change on other days. During the post-crisis sample, the average decline is 1.3 basis points, which is almost 25% below the 1.7 basis average decline during the pre-crisis sample. This is mostly due to the fact that the overall level of uncertainty was substantially lower during the post-crisis episode as discussed in Section 2 and shown in Figure 1.

Over the last decade the FOMC made substantial changes to the way the outlook for the economy and interest rates is communicated to the public. Starting in October 2007 the FOMC began releasing economic forecasts of the individual committee members, the Survey of Economic Projections (SEP). However, it was not until April 2011 that the SEP was released on the same day as the FOMC statement; previously, the forecasts were released together with the Minutes three weeks after the meeting. Furthermore, in April 2011 Chairman Ben Bernanke started the tradition of holding regular press conferences at every other FOMC meeting. Finally, from January 2012 onwards the also FOMC started releasing committee members' projections for the appropriate future path of the policy rate, the so-called "dot plot," as part of the SEP. Through these new channels of communication, the Fed presumably has been trying to provide more information about economic fundamentals and the rationale underlying the policy actions. Table 2 shows the summary statistics for FOMC meetings starting in January 2012, i.e., once these major changes in communication were in place. The first column reports statistics for all 48 meetings during this period, while the next two columns are for days with and without the release of the SEP, respectively. The average decline in uncertainty measured over this period was somewhat smaller than the decline measured over the entire post-crisis period, and much smaller compared to the overall decline measured for the full sample. However, that is not very surprising given that the level of uncertainty was generally low throughout the last few years as the economic recovery continued and became more robust.

Interestingly, declines in uncertainty are due mainly to FOMC meetings with SEP release (with a dot plot and press conference), which exhibited an average decline about three times larger than on other FOMC meetings. Similarly, the standard deviation of the change in *mpu* is substantially larger on days with SEP release and press conference. This finding is consistent with the interpretation that the FOMC provides substantially more information on these days, and is able to increase market participants' confidence about the rate outlook. Consistent with this, Boguth, Gregoire, and Martineau (2018) find that more attention is being paid to these particular FOMC meetings.[16] Viewed through the lens of our *mpu* measure we find that since 2012 the new communication tools used by the FOMC have been successful in providing useful information and resolving part of the market's uncertainty.

In order get a better intuitive understanding of the effects of FOMC announcements on uncertainty, it is useful to consider the days with the largest changes in more detail. In Table 3 we list the days with the ten biggest increases and the five biggest declines in *mpu*. To provide some context we include some commentary on what happened on the day, often taken directly from the FOMC statement. In addition, the table reports a measure of the monetary policy surprise, the first principal component of changes in Eurodollar futures rates for contracts expiring over the next four quarters, roughly following the methodology in Nakamura and Steinsson (2018).[17] A positive value of the surprise measure indicates that new information on the day of the FOMC announcement—likely in the FOMC statement or the press conference—caused market participants to revise upward their expectations of the policy path over the next year, suggesting a hawkish policy surprise.[18]

[16] Lucca and Moench (2018) updated their findings on the pre-FOMC announcement drift and found that since the Fed started holding press conferences after certain meetings, excess stock returns are earned only around those meetings and not others.

[17] We use daily changes in futures rates in order to be consistent with our daily measure of policy uncertainty, acknowledging that high-frequency changes around the announcements, based on intraday futures and options, would be preferable as they yield higher precision in policy event studies (Gürkaynak, Sack, and Swanson, 2005).

[18] There is a small caveat to this interpretation: Although we refer to a policy "surprise" as is common in this literature, some of the changes in interest rates might be predictable given past information. That is, part of the rate changes might reflect changes in risk premia, in addition to revisions to policy rate expectations (Miranda-Agrippino, 2016).

For most of the days listed in Table 3, the link between the language used in the FOMC statement and the change in *mpu* seems rather obvious and intuitive. On 9 August 2011 for example the FOMC mentions that "The Committee currently anticipates that economic conditions–including low rates of resource utilization and a subdued outlook for inflation over the medium run–are likely to warrant exceptionally low levels for the federal funds rate at least through mid-2013." This is a very clear and unambiguous signal about keeping the policy rate low for a specific horizon. Not very surprisingly, markets react quite strongly to this very clear forward guidance and the *mpu* measure shows a large fall of 13 basis points. At the same time, the measure of monetary policy surprise indicates that the market largely expected that rates would not move, i.e., the announcement predominantly had a strong effect on second as opposed to first moments. The next two dates in Table 3 indicate that a drop in *mpu* does not necessarily need to be correlated with the monetary policy surprise. On 6 July 1995 the FOMC was cutting the target rate for the first time in three years, clearly signaling a change in the stance of monetary policy. In doing so the FOMC surprised the market as indicated by the relatively large negative value in the measure of monetary policy surprise while at the same time removing uncertainty by using very clear language to indicate that a turning point in the stance of monetary policy has been reached. On the other hand, the aggressive cut of 75 basis points on 18 March 2008 in the middle of the credit crisis removed uncertainty by showing that the FOMC is willing to act, even though the market seemingly expected an even higher cut in the target rate as indicated by the rather large positive value in the measure of monetary policy surprise. Here a positive (hawkish) policy surprise coincided with a substantial reduction in policy uncertainty.

Overall, however, there seems to be a positive relationship between the changes in our *mpu* measure and monetary policy surprises as can be seen from the scatter plot in Figure 4. Table 4 reports the corresponding regression results. The correlation is around 35% (and statistically strongly significant) although it is considerably lower and insignificant during the crisis period (only around 8%) and considerably higher during both the pre- and post-crisis sample periods (47% and 55%, respectively). Over the whole sample period, a more contractionary (larger positive) policy surprise is associated with less of a decline or even an increase in policy uncertainty. In line with the scatter plot, the subsample results indicate that the relationship is strong in both the pre- and post-crisis sample but breaks down during the crisis period (where the slope coefficient becomes insignificant). Notably, the positive relationship between first and second moments of future interest rates is not unique to monetary policy days, though it is slightly stronger on these days than otherwise: The correlation in the full daily sample is around 29%. This positive relationship is mainly driven by the fact that our uncertainty measure is affected by the level of the underlying short rate: At higher level of interest rates, the standard deviation of changes in interest rates over the next year tends to be larger. In other words, an increase in the expected level of future short rates tends to also increase the uncertainly about future short rates, and this positive correlation is even stronger on FOMC days. Therefore, controlling for the policy surprise is important when assessing the financial market transmission of changes in monetary policy uncertainty, and we will do so in Section 4. We also note that our main result about the resolution of uncertainty on FOMC days is not affected by the positive relationship between the uncertainty and the policy surprise: Table 4 shows that the constants of the regression on the policy surprise are negative and significant, and have (up to three decimals) the same values as the sample means reported in Table 1. Uncertainty declines on FOMC days not because on average the actions of the FOMC lead to dovish market surprises (which, in turn would reduce uncertainty), but the decline is robust to controling for the correlation between changes in uncertainty and expectations.

Having documented the pattern of declining uncertainty on FOMC announcements, the natural question to ask next is when uncertainty is actually created. If uncertainty goes down on FOMC days then it must rise on other days as the cumulative resolution of uncertainty on FOMC days is much larger than the decline in uncertainty over the course of our sample period. Specifically, Table 1 reports that the cumulative decline on FOMC days adds up to 3.6 percentage points, while on other days uncertainty increases in total by about 3 percentage points, consistent with the fact shown in Figure 1 that the level of uncertainty declines only a modest 50 basis points over the course of our sample.

Is it possible to pin down when exactly uncertainty is created? One possible hypothesis is based on the fact macroeconomic data releases create substantial volatility in stock and bond markets alike (Fleming and Remolona, 1999; Andersen, Bollerslev, Diebold, and Vega, 2007). Hence, an obvious question to ask is whether *mpu* increases on those days as well. The data does not support this hypothesis: In Appendix A we show that uncertainty on average declines on days with major macroeconomic news, such as the release of the employment report by the Bureau of Labor Statistics. Alternatively, one may ask whether it is possible to link changes in *mpu* to speeches by FOMC members during the intermeeting period and whether they could create uncertainty, given that the content of speeches by different members can differ substantially in terms of the outlook provided for monetary policy. Again, there is no evidence in the data to support this view: We show in Appendix B that *mpu* does not significantly increase on days with speeches of FOMC members; in fact, the average change is essentially zero.

While monetary policy uncertainty does not seem to be caused by or even linked to specific types of macro or policy events, it varies in a systematic way over the course of the intermeeting FOMC period. This is evident in Figure 3 which plots the average change over the FOMC cycle relative to the day before the FOMC meeting, i.e., the average of $mpu_{t+j-1} - mpu_{t-1}$ across all FOMC days t, for each value of j ranging from -14 to $+14$ (since the average FOMC intermeeting cycle is about six weeks or 30 business days).[19] Shaded areas show 95%-confidence intervals using White (1980) standard errors. The significant fall on FOMC meeting days of about two basis points reported in the first column of Table 1 is seen in the figure as the one-day change ($j = 1$). Figure 3 reveals that this decline tends to continue for a second day, meaning that the two-day change around FOMC days is slightly larger than the one-day change. But the most striking pattern is that after this initial drop, *mpu* steadily rises during the following days. The most pronounced increase occurs over the ten business days after the day following the FOMC meeting, i.e., from $j = 2$ to about $j = 12$. At that point, the average change relative to the day before the meeting is close to zero and becomes statistically insignificant.[20]

This pattern in the data suggests that there is a predictable gradual ramp-up in uncertainty between FOMC meetings, with most of the increase occurring during the first two weeks of the intermeeting cycle. The finding of such a ramp-up in *mpu* is robust to the choice of sample period as well as to the treatment of outliers, as we show in Appendix C. Notably, excluding the 50 days with the largest increases in *mpu* still leads to a very similar pattern of uncertainty between FOMC meetings, confirming that the gradual increase in uncertainty is a robust pattern that is not driven by a few specific days.

4 The role of uncertainty in the monetary policy transmission to financial markets

Having established how uncertainty about the future path of short-term rates evolves with FOMC announcement and over the FOMC meeting cycle, we now turn to the important question about the role of uncertainty in the transmission of monetary policy to financial markets.

We run event-study regressions to estimate the financial market effects of FOMC actions, following the approach commonly used in the literature; see, for example, Gürkaynak, Sack, and Swanson (2005) and Nakamura and Steinsson (2018). In Table 5, we regress the daily

[19] With unscheduled FOMC meetings, there may be a possible overlap given the range of days we consider. If another FOMC meeting occurs within this range, this change and subsequent changes are excluded.

[20] The confidence intervals show that around eight days after the FOMC meeting, the change in uncertainty relative to its pre-FOMC level *mpu* is statistically insignificant.

change in various asset prices on two variables that capture the change in the market-perceived distribution of future policy rates. The first regression includes our estimate of the monetary policy surprise (the first principal component of the daily change in rates on the Eurodollar futures contracts expiring one to four quarters ahead; see Section 3). This corresponds to the commonly estimated specification and estimates the effects of changes in the first moment of the distribution of the future policy path. The second regression adds the daily change in *mpu* to capture changes in the second moment. With this specification we are able to estimate the effects of changes in uncertainty on financial markets over and above changes in the expected policy rate path caused by FOMC actions. The top panel of Table 5 reports results for the full sample, while the middle and bottom panels report results for the pre-crisis and post-crisis samples, respectively.

Regressions for changes in the five-year and ten-year Treasury yields show the well-established result that changes in the expected policy path lead to sizeable and significant changes in long-term Treasury yields. When we add the change in uncertainty, Δmpu, we find that only the ten-year yield exhibits a statistically significant response to changes in uncertainty, with a modest increase in R^2 relative to the univariate regression. Moreover, the estimated coefficient of 0.41 implies that a one standard deviation (3 basis point) increase in *mpu* measure raises the ten-year yields by about 1.2 basis points. In the pre-crisis sample, the response of yields to changes in uncertainty is not statistically significant, implying that it is driven by events during and after the crisis. In the post-crisis sample, by contrast, the five-year and ten-year yields show a substantially larger response to changes in uncertainty, which is significant at the 10% and 5%-level, respectively. In this sample, a one standard deviation increase in *mpu* leads to a 1.7 (2.0) basis point increase in the five-year (ten-year) yield. Thus on average, changes in *mpu* have a modest effect on the bond market, over and above the effect of monetary policy surprises. However we should note that some FOMC announcements led to large changes in uncertainty, as documented in Section 3, which can lead to substantial effects on bond markets. For example, the FOMC meeting on August 9, 2011 reduced our *mpu* measure by around 11 basis points. The estimates in Table 5 imply a 10 basis point reduction in the ten-year Treasury yield.

Next we turn our attention to the stock market. The third and fourth column of Table 5 report results for daily returns in the S&P 500 index. The seminal paper that studies the link between monetary policy decisions and stock prices is Bernanke and Kuttner (2005). Our specification is comparable to theirs, though we use different sample periods and, importantly, a different measure of monetary policy surprises: We incorporate information from Eurodollar futures contracts expiring up to 1 year ahead, while Bernanke and Kuttner (2005) use the current month's fed funds futures contract. In the pre-crisis sample, we find the coefficient on the policy surprise to be statistically significant but lower in magnitude to Bernanke and Kuttner (2005). In the full and post-crisis samples, the policy surprise shows no significant relationship with stock returns.[21] Adding the change in monetary policy uncertainty as a second regressor changes the regression estimates substantially. In the pre-crisis sample, the coefficient on the policy surprise is now only marginally significant. The largest changes are in the full and post-crisis samples. Here, the coefficient on the policy surprise changes sign and the coefficient on the change in uncertainty is sizeable and strongly significant. The regression R^2 rises dramatically in both samples. According to the full sample estimates a one standard deviation increase in mpu (3 basis points) reduces stock prices by around 0.6%. In the post-crisis sample, our estimates suggest that a one standard deviation increase in uncertainty reduces stock prices by 0.45%. Overall, changes in policy uncertainty have substantial effects on stock returns.

The next two columns report the effects of changes in uncertainty on the VIX. According to the univariate regression, the VIX tends to increase with a hawkish policy surprise, though this coefficient is significant only in the pre-crisis sample. Similarly to regressions for stock returns, adding the uncertainty surprise substantially affects the regression estimates. In the full sample, the R^2 jumps from zero to 0.26, the coefficient on Δmpu is positive, large, and very strongly significant, and the coefficient on the policy surprise turns negative and strongly significant. According to these estimates, a one standard deviation rise in Δmpu increases the VIX by 1.1 percentage points. As in the case of the other asset prices, the coefficient on the uncertainty surprise is smaller in the pre-crisis period, and the t-statistic is only 1.5. In the post-crisis episode, however, coefficient is even larger, implying a 1.3 percentage point increase in the VIX in response to a one standard deviation increase in mpu. Our results show that since the financial crisis changes in monetary policy uncertainty have been strongly positively associated with changes in the VIX.

The last two columns of Table 5 report the response of a US dollar index, the return on an equal-weighted foreign exchange portfolio that goes long the G9 currencies and short the US dollar.[22] The regression on just monetary policy surprises shows that a contractionary policy surprise leads to an appreciation of the dollar. This is not very surprising as this means

[21] This result is driven by our choice of the daily window, as also noted in Lakdawala and Schaffer (2018). Using a higher frequency intra-day monetary policy surprise measure does give significant effects on stock prices but it does not change how stock prices respond to uncertainty shocks, which is the main focus here.

[22] The return to the dollar index is constructed by forming an equal weighted portfolio of the Australian dollar, the Canadian dollar, the British pound, the euro, the Japanese yen, the New Zealand dollar, the Norwegian krone, the Swedish krona and the Swiss franc. The portfolio is rebalanced monthly but returns are calculated on a daily basis. The portfolio is equivalent to the dollar portfolio for example used in Lustig, Roussanov, and Verdelhan (2011).

that fixed income investments in the dollar are more attractive, potentially increasing the demand for dollar. The response is smaller and only marginally significant in the pre-crisis sample, but becomes larger and strongly significant during the post-crisis period. When we add *mpu* to the regression, the response of the exchange rate to changes in uncertainty for the full sample is significant and substantial, implying an appreciation of the US Dollar when uncertainty goes up. But the coefficient on *mps* also remains significant, again pointing to two distinct dimensions by which FOMC actions affect financial markets. For the full sample, a one standard deviation rise in *mpu* is associated with an appreciation of the dollar by 0.6% against a basket of currencies from major economies. This is just about equal to the daily standard deviation of the return to the dollar portfolio, which means that shocks to *mpu* carry over directly to currency returns in standard deviation terms. However, the response to changes in *mpu* appears to be driven by the crisis period only—during the pre- and post-crisis period the coefficient is less than half in magnitude and becomes only marginally or not significant at all, respectively.

Our results so far have focused on nominal bond yields, whereas a recent literature has investigated and compared the response of real and nominal yields to monetary policy surprises (Hanson and Stein, 2015; Nakamura and Steinsson, 2018). In Table 5 we follow this route, following the specification of Hanson and Stein (2015) (see their Table 1) who use two-day changes in asset prices. The dependent variables we consider are the two-day change in the 5 and 10 year forwards rates, both nominal and real (based on TIPS yields). The monetary policy surprise is now measured as the change in the 2 year Treasury yield. The full sample is now restricted to January 1999 to December 2017, based on the availability of the real forwards data. The pre-crisis sample then runs from January 1999 to June 2007 while the post-crisis sample period, as before, is from July 2009 to December 2017.

Our Hanson-Stein regressions result in bigger estimated effects on the bond market, including substantial and significant effects on real rates. Table 6 shows the results, which for the regressions with only the monetary policy surprise are in line with those of Hanson and Stein (2015): in addition to long-term nominal rates, long-term real rates also respond substantially and significantly to monetary policy surprises. The second column adds the two day change in *mpu* as an additional regressor. Both the five-year and ten-year real forward rates react significantly to changes in *mpu*. The effects are sizeable as well. A one standard deviation increase in *mpu* (almost 5 basis points for the two day change) raises the 5 year real forward rate by 6 basis points and the 10 year real forward rate by 3 basis points. Again, we observe a similar pattern as above. In the pre-crisis sample, the additional effect of *mpu* on real forwards is smaller and insignificant. While in the post-crisis sample the effect is significant for the five year real forward rate but not for the 10 year. Finally, for the full and post-crisis samples there is a substantial increase in R^2 for both nominal and real forward rate regressions when we add *mpu*. Hanson and Stein (2015) posit that the response of long-term real rates is evidence of the effects of monetary policy in driving bond risk-premia. Viewed from this lens, our estimates suggest that FOMC announcements that change uncertainty have an effect on bond risk premia, over and above any direct effect coming from shocks to the level of the policy rate. This is consistent with the results of Bundick, Herriford, and Smith (2017) who documented that changes in their market-based uncertainty measure around FOMC announcements tend to be positively correlated with changes in estimates of the term premium in long-term interest rates.

Our results so far indicate a strong response of asset prices to changes in monetary policy uncertainty during the post-crisis period. Of course, this episode was not a normal period for monetary policy, as the FOMC continued to announce unconventional policies including quantitative easing (QE) and forward guidance (FG). To understand the role of changes in monetary policy uncertainty for the financial market effects of unconventional monetary policies (UMPs), we carry out an event study of the major FOMC announcements. This analysis follows a large literature that uses event studies to estimate the financial market effects of UMP, including for example Gagnon, Raskin, Remache, and Sack (2011), Krishnamurthy and Vissing-Jorgensen (2011) and Bauer and Rudebusch (2014). We use the same daily changes as for the regressions reported in Table 5. We chose the most important QE events for QE1, QE2, the maturity extension program (MEP), and QE3 among those identified in the existing literature; see, for example, Bauer and Neely (2014) and other papers cited in Kuttner (2018). The FG events were identified by Raskin (2013) and Swanson (2017).

Table 7 shows our event-study estimates. The announcements of QE1 in late 2008 and early 2009 had substantial effects on asset prices, as has been extensively documented elsewhere, lowering yields and the dollar, and raising stock prices. These announcements also lowered *mpu* significantly, by about 3-5 standard deviations (estimated over the full sample and reported in the bottom row of the table). That is, the expected path of the future policy rate was not only revised downward due to implicit and explicit signaling effects in these announcements, as evident in the large declines in *mps*, but at the same time the uncertainty around this path was also reduced significntly. These estimates suggest that signaling worked not only through first but also through second moments of the perceived distribution of future policy rates.[23] The announcements about QE2 on November 3, 2010 and the MEP on Septem-

[23]A caveat to this interpretation is that the decline in *mpu* reflects not only changes in uncertainty about the fed funds rate but also about the future LIBOR-OIS spread, which undoubtedly played a role during this heightened financial stress episode.

ber 21, 2011, had smaller and more mixed effects on financial markets. Another major FOMC policy action was the FG announcement on August 9, 2011, when the FOMC indicated that it would like keep the policy rate near zero "at least through mid-2013" and began a phase of calendar-based FG. In response there was a modestly negative policy surprise of about negative 5 basis points, but a dramatic decline in policy uncertainty, indeed the largest decline in *mpu* in our sample. Treasury yields plummeted, the stock market jumped, with a historically large decline in the VIX of 13 percentage/index points, and the dollar depreciated 1.5 percent against other major currencies. These large asset price responses, strongly significant based on the reported standard deviations, appear to have been caused by the Fed's explicit FG language through its effects on the perceived distribution of the future policy rate. In this instance, when the policy rate was already at the zero lower bound and expected to remain there for the near future, changes in the second moment of this distribution were at least as important as changes in the first moment caused by the announcement. Other FG announcements also generally reduced policy uncertainty and supported financial market conditions. By contrast, the "taper tantrum"—the episode in mid-2013 of increased speculation about the timing of the end of QE, caused by public remarks of Chairman Bernanke about the tapering of asset purchases—increased uncertainty and tightened financial conditions. Around the FOMC announcement and press conference on June 19, 2013 policy uncertainty increased together with expectations for the future policy rate, while Treasury yields jumped and stock prices declined. Finally we note the SEP releases coinciding with the FOMC announcements in March and September 2015, which are discussed in more detail in Swanson (2017). Both featured dovish interest rate projections relative to market expectations, and lowered both the expected path as well as the uncertainty around this path, according to our estimates. Long-term Treasury yields fell significantly in response, a final example of the impact of forward guidance, this time in the form of the SEP dot plot, on financial conditions.

Our findings support the view that monetary policy expectations have two distinct dimensions, both of which are affected by the FOMC's policy actions: the *level* of the expected policy path and the *uncertainty* around this future path. In studying the transmission to financial markets, the existing literature has mainly focused on the first dimension. By contrast, we document the important role of changes in uncertainty, a separate channel for the transmission of monetary policy, in particular when it comes to long-term assets such as Treasury bonds and stocks. Our results suggest that the FOMC may have an additional lever for affecting asset prices and financial conditions, namely by influencing the market's perceived uncertainty about the future path of the short rate. The evidence shows that this second dimension is particularly relevant when it comes to the FOMC's forward guidance.

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Table 1: Summary statistics for changes in monetary policy uncertainty

	Jan-1994 to Dec-2017		Jan-1994 to Jun-2007		Jul-2009 to Dec-2017	
	FOMC	Non-FOMC	FOMC	Non-FOMC	FOMC	Non-FOMC
No. of observations	203	5789	112	3252	68	2060
Mean	-0.018	0.001	-0.017	0.000	-0.013	0.000
Median	-0.013	-0.000	-0.012	0.000	-0.009	-0.000
Standard deviation	0.032	0.024	0.028	0.021	0.025	0.020
Minimum	-0.132	-0.280	-0.128	-0.131	-0.132	-0.132
Maximum	0.118	0.352	0.048	0.208	0.040	0.113
Cumulative change	-3.656	3.036	-1.865	1.605	-0.859	0.126
Null hypothesis:						
$\mu^{FOMC} = 0$	0.000		0.000		0.000	
$\mu^{Non-FOMC} = 0$	0.099		0.187		0.892	
$\mu^{FOMC} = \mu^{Non-FOMC}$	0.000		0.000		0.000	

Summary statistics for changes in *mpu*, the market-based standard deviation for the short-term interest rate one year into the future, measured in percentage points. Bottom panel reports *p*-values for *t*-tests about the mean μ using White heteroscedasticity-robust standard errors.

Table 2: Summary statistics for changes in monetary policy uncertainty since 2012

	All FOMC	FOMC with SEP	FOMC without SEP
No. of observations	48	25	23
Mean	-0.008	-0.013	-0.003
Median	-0.006	-0.013	-0.004
Standard deviation	0.016	0.018	0.011
Minimum	-0.046	-0.046	-0.026
Maximum	0.027	0.027	0.027
Cumulative change	-0.391	-0.318	-0.073
Null hypothesis:			
$\mu = 0$	0.001	0.002	0.175
$\mu^{SEP} = \mu^{Non-SEP}$		0.000	

Summary statistics for the change in *mpu* on FOMC meeting days from January 2012 to December 2017. The first column is based on all meetings, while the next two columns split the meetings based on whether the Survey of Economic Projections (SEP) was released. Bottom panel reports *p*-values for *t*-tests about the mean μ using White heteroscedasticity-robust standard errors.

Table 3: FOMC announcements and the largest changes in policy uncertainty

Top 10 increases in monetary policy uncertainty

Meeting date	Δmpu	mps	Description
09 Aug 2011	-0.132	-0.046	Clear forward guidance and indication that rates will be kept low for at leat another two years: "...warrant exceptionally low levels for the federal funds rate at least through mid-2013."
06 Jul 1995	-0.128	-0.235	First cut in 3 years signaling a change in the stance of monetary policy: "...inflationary pressures have receded enough to accommodate a modest adjustment in monetary conditions."
18 Mar 2008	-0.124	0.252	Fed funds target rate cut aggressively by 75bps.
16 Dec 2008	-0.114	-0.321	ZLB is reached and clear forward guidance: "...weak economic conditions are likely to warrant exceptionally low levels of the federal funds rate for some time."
17 Nov 1998	-0.112	-0.030	Third cut in a row and signal that there may not be further cuts: "...financial conditions can reasonably be expected to be consistent with fostering sustained economic expansion..."
11 Mar 2008	-0.098	0.214	No FOMC meeting but announcement of TSLF "...to promote liquidity in the financing markets for Treasury and other collateral..."
25 Nov 2008	-0.098	-0.171	Last meeting before reaching ZLB. Announcement of TALF "designed to increase credit availability and support economic activity by facilitating renewed issuance of consumer and small business ABS at more normal interest rate spreads."
06 May 2003	-0.090	-0.089	No change in monetary policy stance.
15 Oct 1998	-0.084	0.086	Second of three 25bps cuts in a row. Confirmation that the Fed is further easing the stance of monetary policy.
30 Jan 2008	-0.076	-0.049	Fed funds target rate cut by 50bps a week after a 75bps cut in an emergency meeting.
18 Mar 2009	-0.075	-0.274	Announcement of QE1 expansion to buy "...an additional $750 billion of agency mortgage-backed securities" and to "purchase up to $300 billion of longer-term Treasury securities..."

Top 5 declines in monetary policy uncertainty

Meeting Date	Δmpu	mps	Comment and/or FOMC statement
08 Oct 2008	0.118	0.073	Concerted actions by central banks around the world: "...the Bank of Canada, the Bank of England, the European Central Bank, the Federal Reserve, Sveriges Riksbank, and the Swiss National Bank are today announcing reductions in policy interest rates."
28 Jan 2004	0.048	0.136	FOMC meeting 6 months after the last cut and 6 months before the next raise. Balanced outlook: "...the upside and downside risks to the attainment of sustainable growth for the next few quarters are roughly equal."
27 Jan 2010	0.040	0.047	The FOMC "...is gradually slowing the pace of..." asset purchases as previously announced.
18 Apr 2001	0.037	0.241	One of a series of 50bps cuts in 2001 as "...the risks are weighted mainly toward conditions that may generate economic weakness in the foreseeable future."
26 Jun 2002	0.031	-0.146	No change in monetary policy stance but large negative monetary policy surprise.

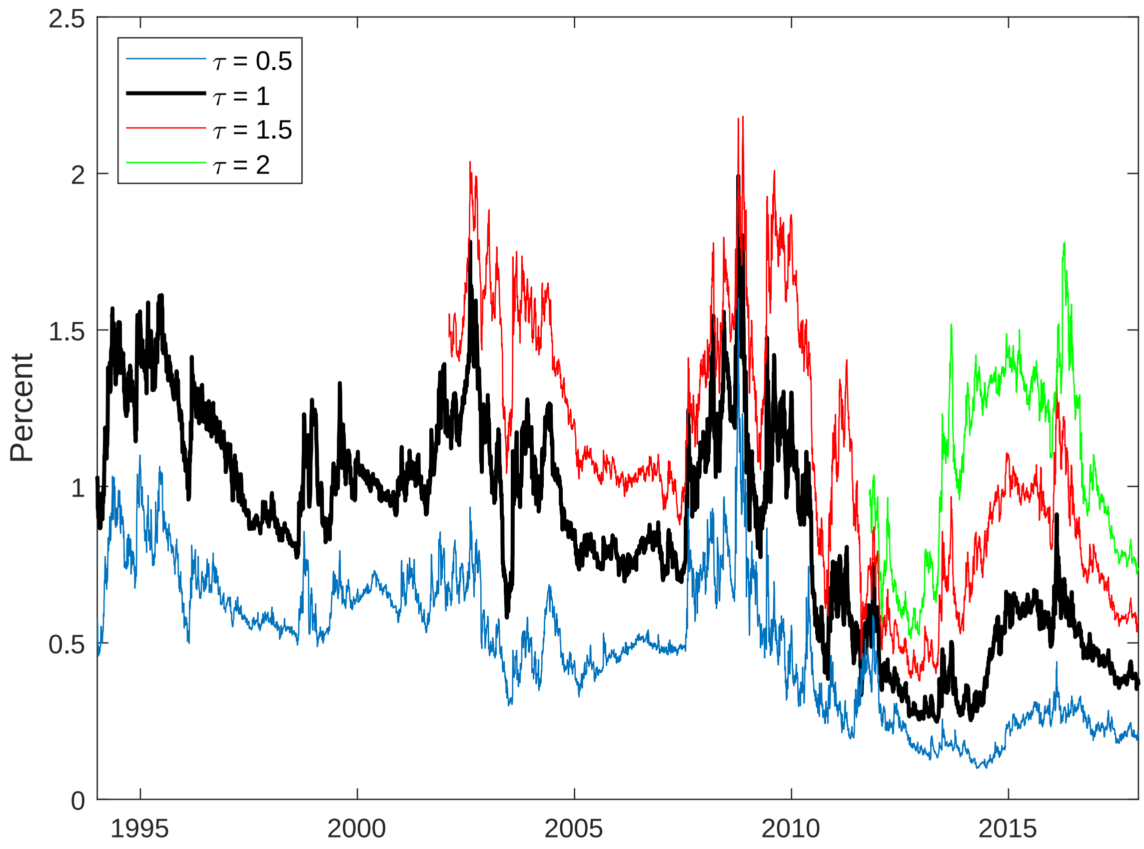
The 10 largest delines and five largest increases in monetary policy uncertainty, mpu, along with the monetary policy surprise, mps, and a brief narrative taken from the FOMC statement. For details see the main text.

Table 4: Regressions of change in uncertainty on policy surprise

	Jan-94 to Dec-17	Jan-94 to Jun-07	Jul-09 to Dec-17
Policy surprise	0.130	0.149	0.294
	[2.96]	[3.59]	[4.37]
Constant	-0.018	-0.017	-0.013
	[-8.64]	[-7.11]	[-4.96]
Observations	203	112	68
R^2	0.121	0.217	0.289

Results for regressions of the daily change in *mpu* on the policy surprise measure on days with FOMC announcements. In squared brackets are *t*-statistics based on White heteroscedasticity-robust standard.

Figure 1: Option-based estimate of monetary policy uncertainty



Risk-neutral standard deviation of three-month LIBOR rate at horizon of τ years, estimated from Eurodollar futures and options. Sample period: 1/3/1994 to 1/29/2018.

Table 5: Response of asset prices to changes in uncertainty and policy surprise

	Full Sample: Jan-1994 to Dec-2017 (203 observations)									
	Five-year yield		Ten-year yield		S&P 500		VIX		Dollar Index	
Policy surprise	0.75	0.71	0.56	0.50	-0.02	0.01	0.15	-4.27	-0.03	-0.02
	[10.34]	[9.93]	[6.20]	[5.99]	[-0.81]	[0.52]	[0.06]	[-2.05]	[-4.40]	[-3.65]
Chg. in uncertainty		0.28		0.41		-0.19		33.99		-0.06
		[1.33]		[1.98]		[-4.00]		[4.44]		[-3.94]
R^2	0.54	0.55	0.35	0.38	0.01	0.16	0.00	0.26	0.17	0.25

	Pre-crisis sample: Jan-1994 to Jun-2007 (108 observations)									
	Five-year yield		Ten-year yield		S&P 500		VIX		Dollar Index	
Policy surprise	0.61	0.57	0.44	0.40	-0.04	-0.03	3.12	1.64	-0.01	0.00
	[12.58]	[10.81]	[7.98]	[6.83]	[-3.08]	[-1.76]	[2.36]	[0.94]	[-1.71]	[-0.70]
Chg. in uncertainty		0.22		0.28		-0.04		9.88		-0.03
		[1.51]		[1.70]		[-0.59]		[1.50]		[-1.87]
R^2	0.65	0.65	0.46	0.48	0.10	0.10	0.06	0.11	0.04	0.08

	Post-crisis Sample: Jul-2009 to Dec-2017 (68 observations)									
	Five-year yield		Ten-year yield		S&P 500		VIX		Dollar Index	
Policy surprise	1.04	0.84	0.69	0.46	-0.04	0.01	9.08	-6.70	-0.10	-0.09
	[7.16]	[5.92]	[3.85]	[2.55]	[-1.37]	[0.26]	[1.40]	[-1.09]	[-6.15]	[-5.12]
Chg. in uncertainty		0.67		0.80		-0.18		53.68		-0.02
		[1.90]		[1.97]		[-2.06]		[2.31]		[-0.72]
R^2	0.42	0.45	0.20	0.25	0.04	0.18	0.04	0.35	0.44	0.45

Regressions of daily changes in the five-year and ten-year Treasury yields, returns in the S&P500 index, changes in the VIX index and returns to the dollar index (constructed by forming an equal weighted portfolio of nine major currencies, see text) on the monetary policy surprise (first moment) and the change in uncertainty (second moment) on FOMC announcement days. The t-statistics, based on White heteroscedasticity-robust standard errors, are reported in parentheses.

Table 6: Response of Treasury forward rates to MP uncertainty and MP surprise

	Nominal Forwards				Real Forwards			
	Full Sample: Jan-1999 to Dec-2017 (161 observations)							
	Five-year		Ten-year		Five-year		Ten-year	
Policy surprise	1.07	0.82	0.51	0.34	1.05	0.81	0.50	0.39
	[6.99]	[7.00]	[3.81]	[2.85]	[5.92]	[5.63]	[5.78]	[4.76]
Chg. in uncertainty		1.38		0.88		1.28		0.60
		[5.02]		[2.76]		[4.25]		[2.79]
R^2	0.34	0.50	0.10	0.20	0.33	0.48	0.17	0.24
	Pre-crisis Sample: Jan-1999 to June-2007 (70 observations)							
	Five-year		Ten-year		Five-year		Ten-year	
Policy surprise	0.75	0.54	0.46	0.28	0.76	0.70	0.46	0.39
	[7.56]	[4.52]	[4.78]	[2.11]	[6.40]	[5.75]	[5.46]	[3.97]
Chg. in uncertainty		1.27		1.06		0.32		0.39
		[3.34]		[2.44]		[1.21]		[1.48]
R^2	0.37	0.52	0.17	0.30	0.54	0.55	0.29	0.32
	Post-crisis Sample: Jul-2009 to Dec-2017 (68 observations)							
	Five-year		Ten-year		Five-year		Ten-year	
Policy surprise	1.80	1.28	0.59	0.38	1.62	0.97	0.82	0.61
	[6.19]	[4.73]	[1.89]	[1.15]	[7.28]	[4.67]	[3.50]	[2.56]
Chg. in uncertainty		1.02		0.42		1.27		0.41
		[2.34]		[0.86]		[3.48]		[0.96]
R^2	0.40	0.44	0.06	0.07	0.46	0.56	0.17	0.18

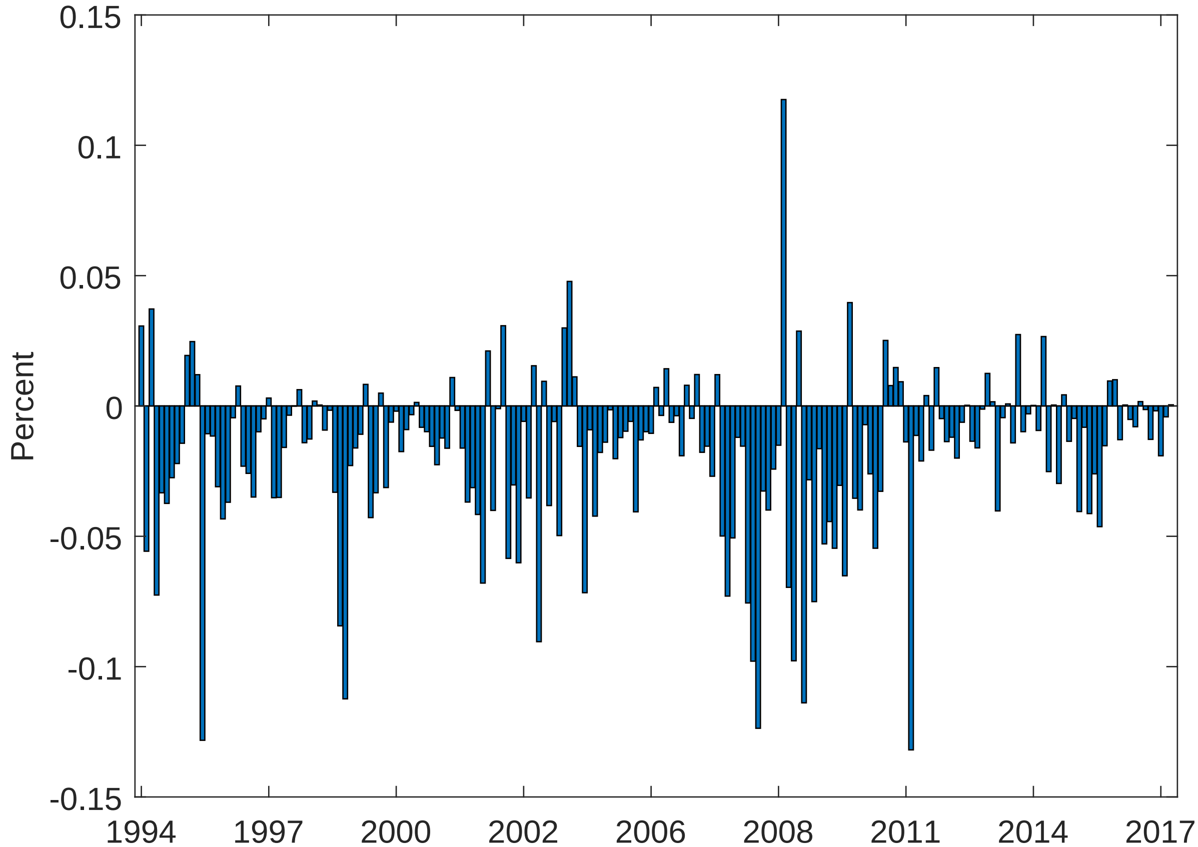
The table shows regressions of Treasury forward rates on change in uncertainty (*mpu*) and the monetary policy surprise (*mps*) on FOMC announcement days. The specification follows Hanson and Stein (2015) and uses the two day change in the forward rates, uncertainty and the policy surprise. In this table, different from the rest of our analysis, *mps* is measured using the two year Treasury yield, as in Hanson and Stein (2015). For each dependent variable, the first column has results from only policy surprise as a regressor, while the second column has results for both change in uncertainty and policy surprise as regressors. t-statistics based on White heteroscedasticity-robust standard errors are reported in parentheses.

Table 7: Event study of quantitative easing and forward guidance

Date	Event	Δmpu	mps	5y yld.	10y yld.	S&P 500	VIX	Dollar
11/25/2008	QE1	-0.098	-0.171	-0.225	-0.214	0.007	-3.800	0.007
12/16/2008	QE1/FG	-0.114	-0.321	-0.163	-0.175	0.050	-4.390	0.023
3/18/2009	QE1/FG	-0.075	-0.274	-0.471	-0.519	0.021	-0.740	0.028
11/3/2010	QE2	-0.033	-0.003	-0.040	0.041	0.004	-2.010	0.006
8/9/2011	FG	-0.132	-0.046	-0.191	-0.205	0.046	-12.940	0.015
9/21/2011	MEP	-0.011	0.060	0.018	-0.084	-0.030	4.460	-0.016
1/25/2012	FG	-0.017	-0.002	-0.094	-0.080	0.009	-0.600	0.005
9/13/2012	QE3/FG	-0.020	-0.002	-0.037	-0.029	0.016	-1.750	0.005
12/12/2012	FG	0.000	0.011	0.023	0.057	0.000	0.380	0.002
6/19/2013	Taper tantrum	0.012	0.038	0.170	0.137	-0.014	0.030	-0.009
12/17/2014	FG	-0.025	0.027	0.083	0.078	0.020	-4.130	-0.010
3/18/2015	FG	-0.030	-0.079	-0.153	-0.119	0.012	-1.690	0.019
9/17/2015	FG	-0.041	-0.083	-0.116	-0.090	-0.003	-0.210	0.005
Std. dev. (full sample)		0.025	0.015	0.061	0.060	0.012	1.565	0.005

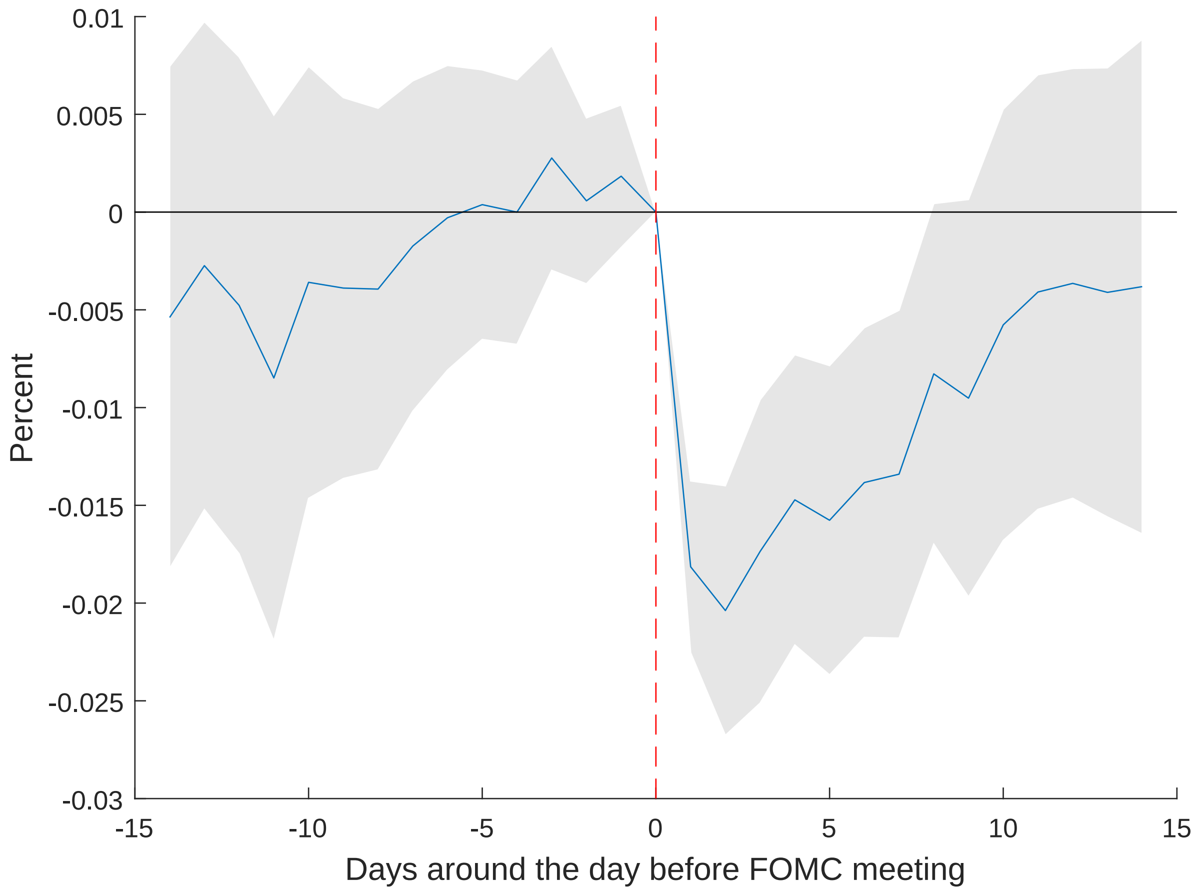
Changes in asset prices on selected days with major FOMC announcements about unconventional monetary policy, including the three large-scale asset purchase programs, or quantitative easing (QE), the maturity extension program (MEP), and forward guidance (FG). Δmpu are daily changes in our measure of monetary policy uncertainty, mps is the monetary policy surprise based on changes in Eurodollar futures rates.

Figure 2: Changes in policy uncertainty on FOMC announcement days



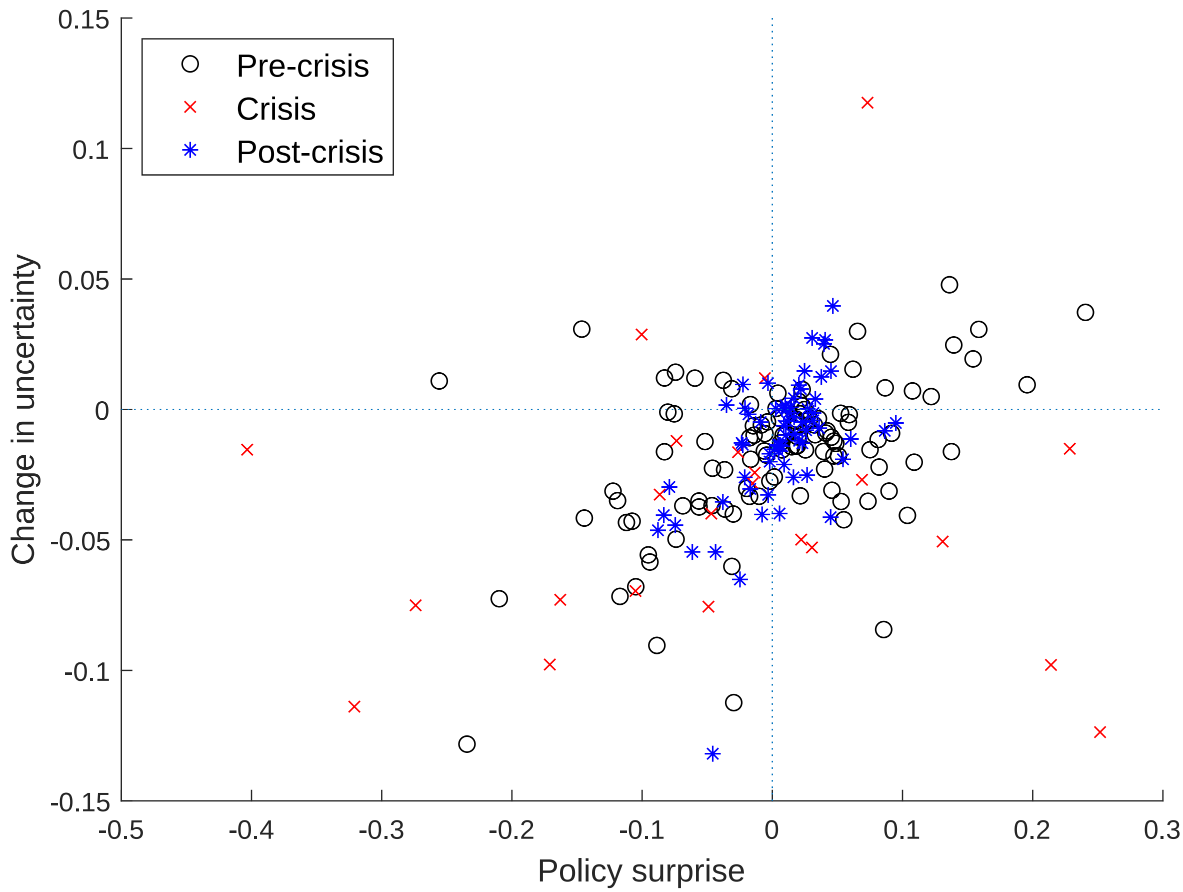
Daily change in monetary policy uncertainty on days with FOMC announcements. The sample includes 203 FOMC announcements form January 1994 to December 2017.

Figure 3: Changes in policy uncertainty over the FOMC meeting cycle



The figure shows the average change in policy uncertainty relative to the day before the FOMC meeting day. The shaded gray shaded region shows 95% confidence intervals constructed using White heteroscedasticity-robust standard errors. The sample includes 203 FOMC announcements form January 1994 to December 2017.

Figure 4: Monetary policy surprise and change in policy uncertainty



Scatter plot of the change in policy uncertainty against the policy surprise on FOMC announcment days. The pre-crisis sample is Jan 1994 to Jun 2007, the crisis period is taken to be from July 2007 to June 2009, and our post-crisis sample is from July 2009 to December 2017.

A Do macro news releases increase monetary policy uncertainty?

Here we investigate the question whether the releases of macroeconomic data lead to increases in uncertainty. We focus our attention on macro news releases that get the most attention in the media and the financial markets. Following Bauer (2015) we consider three main categories:

- Days on which the Bureau of Labor Statistics releases its employment report,
- days with a release of either the Consumer Price Index (CPI) or the Producer Price Index (PPI), and
- days with new retail sales numbers.

Table A.1 shows the summary statistics for the change in monetary policy uncertainty on these news days, in comparison to the FOMC days. On average, uncertainty *falls* on these macro news days, but with an average fall that is an order of magnitude smaller relative to FOMC days. The standard deviation on days with an employment report days is substantially higher than on FOMC days, with the largest increase in uncertainty occurring after the June 2009 report showed a decline of 467,000 jobs. The standard deviation on CPI/PPI days and retail Sales days is lower relative to FOMC days.[24] This evidence suggests that macro news releases tend to resolve uncertainty, as opposed to the hypothesis that they create additional uncertainty about future interest rates. Macro news cannot explain the rise in uncertainty outside of FOMC days.

Table A.1: Summary statistics for policy/macro data announcement days

	FOMC	Employment	CPI/PPI	Retail sales
No. of observations	192	281	570	286
Mean	-0.019	-0.006	-0.004	-0.002
Median	-0.015	-0.009	-0.003	-0.001
Standard deviation	0.030	0.042	0.027	0.023
Minimum	-0.166	-0.124	-0.166	-0.088
Maximum	0.061	0.389	0.131	0.095
Cumulative change	-3.626	-1.595	-2.030	-0.656

Summary statistics for the change in policy uncertainty on major macro news release days in addition to FOMC announcement days.

[24] In addition to the average change in uncertainty on news days, we also considered whether the surprise component of the news release is correlated with changes in policy uncertainty. We did not find any systematic relationship between the macro surprises and the change in policy uncertainty.

B Do speeches by FOMC participants increase uncertainty?

Another possibility is that speeches given by Fed policy makers could be creating uncertainty about future short rates. To explore this, in Table B.1 below we show the summary statistics for changes in *mpu* on days when these speeches were made. The first column considers a speech given by all FOMC members, including governors and presidents. The last three columns focus on the last three Fed chair speech days. As is clear from the table, the mean change in *mpu* on days with speeches is negligible. This rules out the possibility that the uncertainty that is resolved with FOMC announcements is being created on speech days.

Table B.1: Summary statistics for days with speeches by FOMC members

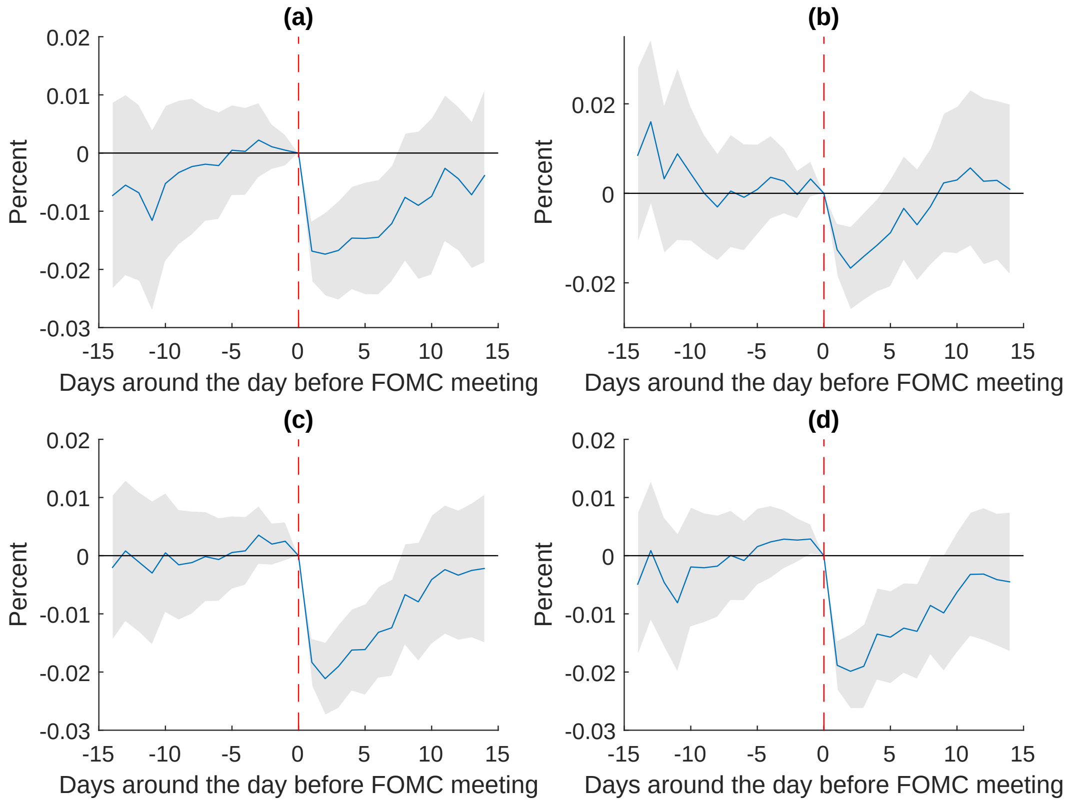
	All speeches	Greenspan	Bernanke	Yellen
No. of observations	2130	119	156	57
Mean	0.000	-0.003	0.002	-0.003
Median	0.000	-0.001	0.001	0.000
Standard deviation	0.025	0.017	0.037	0.017
Minimum	-0.280	-0.062	-0.280	-0.065
Maximum	0.352	0.038	0.170	0.031
Cumulative change	0.756	-0.304	0.285	-0.152

Summary statistics for the change in policy uncertainty on Fed speech days. The first column considers a speech given by any member of the FOMC. The last three columns focus on the last three Fed chair speech days. The sample period is from January 1994 to December 2017.

C Robustness of uncertainty ramp-up between FOMC meetings

In this section we document that the pattern of the resolution of uncertainty on FOMC days and the subsequent rise in the inter-meeting period is result that is robust across a variety of dimensions. We present four robustness checks in figure C.1. The top left panel (labeled "(a)") shows the pattern for the pre-crisis sample of January 1994 to June 2007, while the top right panel (labeled "(b)") shows it for the post-crisis sample of July 2009 to December 2017. Both these figures show the same result of a clear and significant resolution of uncertainty on the day of the FOMC announcement, followed by a gradual ramp-up in the following two weeks. As we discussed in the main text, the fall in *mpu* on FOMC meeting days is lower in the post-crisis sample owing to the overall lower level of uncertainty in that sample. The bottom left panel (labeled "(c)") shows the pattern excluding unscheduled meetings from our sample, with no discernible effects on the results. Finally, we have checked to make sure that outliers are not driving this pattern. To be even more cautious, we tabulate the dates with the 50 biggest increases in *mpu*. Excluding these 50 dates also does not materially change the

Figure C.1: Changes in policy uncertainty over the FOMC meeting cycle



Average change in *mpu* relative to the day before the FOMC meeting day. Panel (a) restricts the sample to pre-crisis dates of January 1994 to June 2007. Panel (b) restricts the sample to post-crisis dates of July 2009 to December 2017. Panel (c) uses the full sample but drops unscheduled FOMC announcements. Panel (d) drops the 50 largest increases in *mpu*. The shaded gray shaded region shows 95% confidence intervals constructed using White heteroscedasticity-robust standard errors.

results, which are also presented in bottom right panel (labeled "(d)". Thus it appears that the documented rise in *mpu* is not being driven by any specific days but instead appears to be a gradual increase in uncertainty in between FOMC meetings.